hep-ph/0002172
February 16, 2000

Search for TeV Strings and New Phenomena in Bhabha Scattering at LEP2

Dimitri Bourilkov*

Institute for Particle Physics (IPP), ETH Zürich,
CH-8093 Zürich, Switzerland

Abstract

A combined analysis of the data on Bhabha scattering at centre-of-mass energies 183 and 189 GeV from the LEP experiments ALEPH, L3 and OPAL is performed to search for effects of TeV strings in quantum gravity models with large extra dimensions. No statistically significant deviations from the Standard Model expectations are observed and lower limit on the string scale $\mathrm{M_S} = 0.631$ TeV at 95 % confidence level is derived. The data are used to set lower limits on the scale of contact interactions ranging from 4.2 to 16.2 TeV depending on the model. In a complementary analysis we derive an upper limit on the electron size of $2.8 \cdot 10^{-19}$ m at 95 % confidence level.

*e-mail: Dimitri.Bourilkov@cern.ch

Introduction

The Standard Model (SM) is very successful in confronting the data coming from the highest energy accelerators. Still, there are theoretical reasons to expect that it is not complete, and one of the first questions in the quest for new physics is what is the relevant scale, where new phenomena can give experimental signatures. Recently, a radical proposal [1–3] has been put forward for the solution of the hierarchy problem, which brings close the electroweak scale $\mathrm{m_{EW}} \sim 1$ TeV and the Planck scale $\mathrm{M_{Pl}} = \frac{1}{\sqrt{\mathrm{G_N}}} \sim 10^{15}$ TeV. In this framework the effective four-dimensional $\mathrm{M_{Pl}}$ is connected to a new $\mathrm{M_{Pl(4+n)}}$ scale in a (4+n) dimensional theory:

$$\mathrm{M_{Pl}^2} \sim \mathrm{M_{Pl(4+n)}^{2+n}} \mathrm{R^n} \tag{1}$$

where there are n extra compact spatial dimensions of radius $\sim$ R. This can explain the observed weakness of gravity at large distances. At the same time, quantum gravity becomes strong at a scale M of the order of 1 TeV and could have observable signatures at present and future colliders.

The first experimental searches for large extra dimensions have concentrated on the effects of real and virtual graviton emission[1]. In a string theory of quantum gravity [7,8] there are additional modifications of Standard Model amplitudes and new phenomenological consequences. Effective contact interactions caused by massive string mode oscillations might compete with or even become stronger than those due to virtual exchange of Kaluza-Klein excitations of gravitons, and thus provide the first signature of low scale gravity or a lower bound on the string scale.

Bhabha scattering above the Z resonance offers a reach hunting field for new phenomena [6, 9]. It can be used to search for manifestations of contact interactions and as a very sensitive probe of the point-like structure of the electron.

This paper is organized as follows. In sections 2 and 3 the experimental data and the analysis technique are presented. In the following section, we describe the search for effects of TeV strings in Bhabha scattering. In sections 5 and 6 we use the data to obtain limits on the scale of different contact interaction models, and on the size of electrons respectively. We conclude with a discussion of the results.

Experimental Data

Data on fermion-pair production at 183 or 189 GeV centre-of-mass energies from the LEP2 collider has become available recently. In the following we will concentrate on the measurements of Bhabha scattering at these two highest energy points, where large data samples have been accumulated during the very successful LEP runs in 1997 and 1998.

The ALEPH [10], L3 [11] and OPAL [12,13] collaborations have presented results for the differential cross section of Bhabha scattering. In the case of L3 and OPAL the results are for both energy points and the scattering angle θ is the angle between the incoming and the outgoing electrons in the laboratory frame. In the ALEPH case the measurements are at 183 GeV and the scattering angle is defined in the outgoing $\mathrm{e^+e^-}$ rest frame. The acceptance is given by the angular range $|\cos\theta| < 0.9$ for the ALEPH and OPAL measurements and by $44° < \theta < 136°$ for the L3 measurement.

The experiments use different strategies to isolate the high energy sample, where the interactions take place at energies close to the full available centre-of-mass energy. This sample is

[1] For searches in Bhabha scattering see e.g. [4–6].

the main search field for new physics. L3 and OPAL apply an acollinearity cut of 25° and 10° respectively. ALEPH defines the effective energy, $\sqrt{s'}$, as the invariant mass of the outgoing fermion pair. It is determined from the angles of the outgoing fermions. For details of the selection procedures, the statistical and systematic errors we refer the reader to the publications of the LEP experiments.

Analysis Method

The Standard Model predictions for the differential cross sections of Bhabha scattering at 183 and 189 GeV are computed with the Monte Carlo generator BHWIDE [14]. We assign a theory uncertainty of 1.5 % on the absolute scale of the predictions. In all cases the individual experimental cuts of the selection procedures and the isolation of the high energy samples are taken into account. The results are cross-checked with the semi-analytic program TOPAZ0 [15].

The effects of new phenomena are computed as a function of a generic parameter ε, defined for each individual case in the corresponding section. Initial-state radiation (ISR) changes the effective centre-of-mass energy in a large fraction of the observed events. We take these effects into account by computing the first order exponentiated differential cross section following [16]. Other QED and electroweak corrections give smaller effects and are neglected.

In total we have 47 data points: 28 from the 3 differential spectra at 183 GeV and 19 from the L3 and OPAL spectra at 189 GeV. A fitting procedure similar to the one in [6,17] is applied.

A negative log-likelihood function is constructed by combining all data points at the two centre-of-mass energies:

$$-\log\mathcal{L} = \sum_{r=1}^{n}\left(\frac{(\mathrm{Prediction}(\mathrm{SM},\varepsilon)-\mathrm{Measurement})^2}{2\cdot\Delta^2_{\mathrm{Measurement}}}\right)_r \tag{2}$$

$$\Delta_{\mathrm{Measurement}} = \mathrm{error}(\mathrm{Prediction}(\mathrm{SM},\varepsilon)-\mathrm{Measurement}) \tag{3}$$

where $Prediction(SM,\varepsilon)$ is the SM expectation for a given measurement (a point in the differential spectra) combined with the additional effect of new phenomena as a function of the mass scale or electron size, and $Measurement$ is the corresponding measured quantity. The index r runs over all data points. The error on a deviation consists of three parts, which are combined in quadrature: a statistical error and a systematic error (as given by the experiments) and the theoretical error assigned above. The systematic errors account for small correlations between data points.

TeV Strings in Bhabha Scattering

In [8] the authors develop a model to study the effects of string Regge excitations on physical cross sections by a simple embedding of the Quantum Electrodynamics of electrons and photons into string theory. They use only one gauge group and only vector-like couplings, in order to avoid complications but grasp the general phenomenological picture. The results are model-dependent.

The effects of TeV scale strings on Bhabha scattering are computed from the leading-order scattering amplitudes. All amplitudes are multiplied by a common form-factor

$$\mathcal{S}(\mathrm{s},\mathrm{t}) = \frac{\Gamma(1-\frac{\mathrm{s}}{\mathrm{M_S^2}})\Gamma(1-\frac{\mathrm{t}}{\mathrm{M_S^2}})}{\Gamma(1-\frac{\mathrm{s}}{\mathrm{M_S^2}}-\frac{\mathrm{t}}{\mathrm{M_S^2}})}. \tag{4}$$

In the case where the string scale M_S is close to or smaller than the centre-of-mass energy, the Gamma-functions in this form-factor produce a very reach and complicated resonance structure. On the other hand, in the limit where the Mandelstam variables s and t are much smaller than M_S, we have

$$\mathcal{S}(s,t) = (1 - \frac{\pi^2}{6}\frac{st}{M_S^4} + ...). \tag{5}$$

So in this model the leading corrections are proportional to M_S^{-4}, corresponding to an operator of dimension 8.

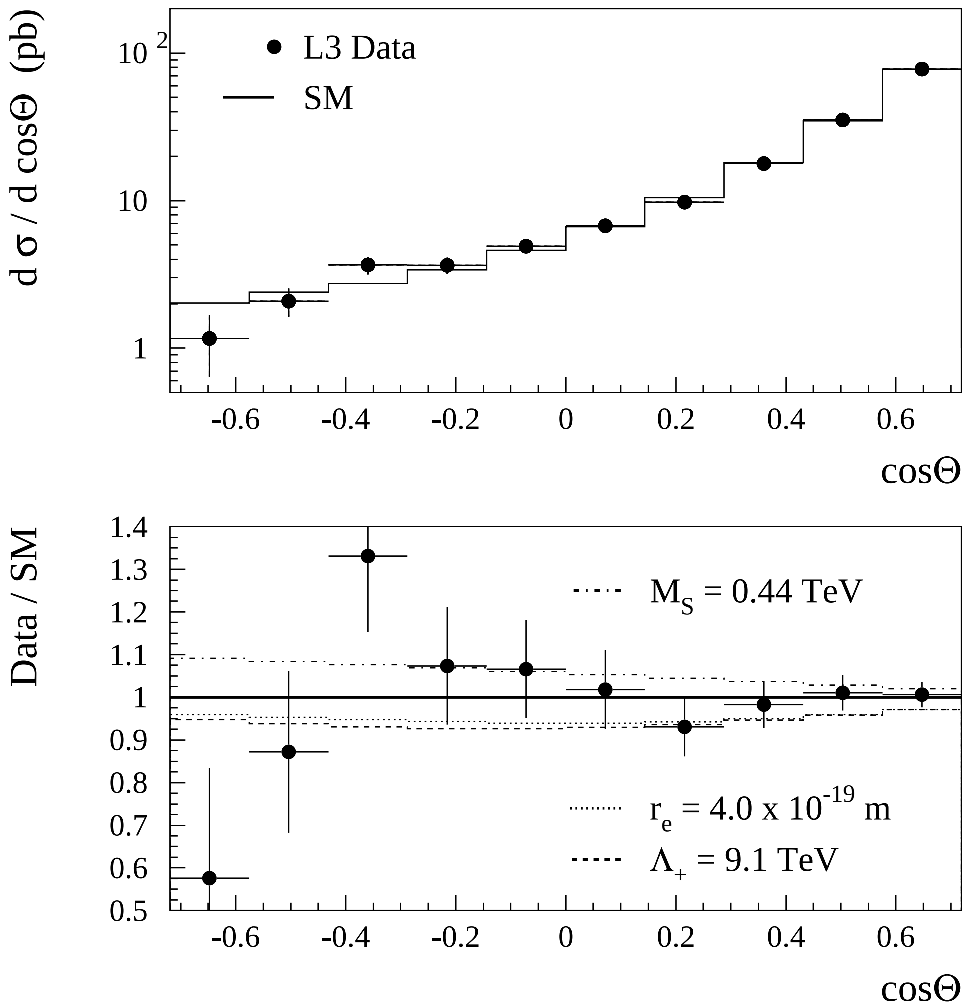

Figure 1: *The differential cross section for Bhabha scattering as measured by the L3 collaboration at 189 GeV. The lower plot shows the ratio (data/SM expectation) together with the expected deviations from the SM for string models (dot-dash), finite electron size (dotted) and VV contact interactions (dashed).*

To compare the string predictions to the data on Bhabha scattering above the Z resonance one has to handle also the contributions due to Z exchange and the interference with photon exchange amplitudes. The Z is not part of the string QED model developed in [8], but as all

QED Bhabha scattering amplitudes are multiplied by the common factor $\mathcal{S}(\mathrm{s},\mathrm{t})$, the authors suggest to compare the differential cross section to the simple formula

$$\frac{\mathrm{d}\sigma}{\mathrm{dcos}\,\theta} = (\frac{\mathrm{d}\sigma}{\mathrm{dcos}\,\theta})_{\mathrm{SM}} \cdot |\mathcal{S}(\mathrm{s},\mathrm{t})|^2. \tag{6}$$

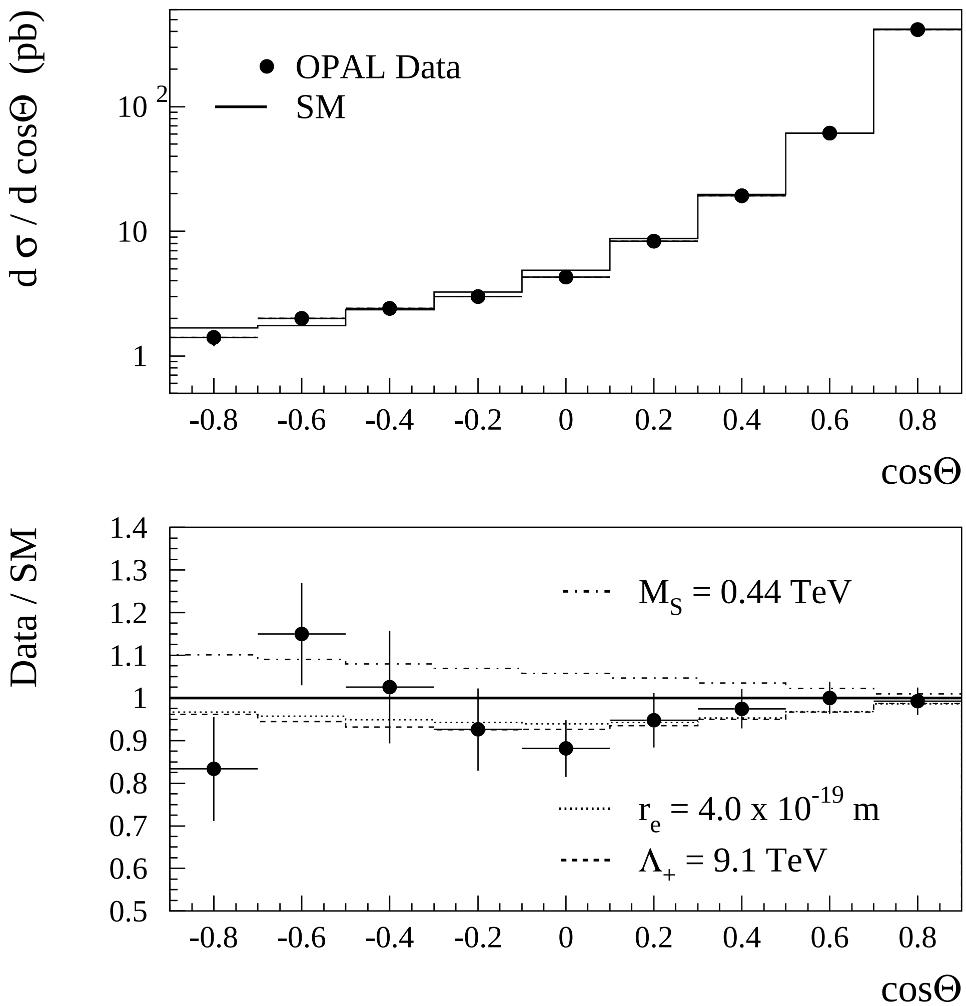

Figure 2: *The differential cross section for Bhabha scattering as measured by the OPAL collaboration at 189 GeV. The lower plot shows the ratio (data/SM expectation) together with the expected deviations from the SM for string models (dot-dash), finite electron size (dotted) and VV contact interactions (dashed).*

The data from the LEP collaborations at 183 and 189 GeV show no statistically significant deviations from the SM predictions due to string effects. In their absence, we use the log-likelihood method, which after proper normalization gives the confidence level for any value of the scale $\mathrm{M_S}$ in the physically allowed region. The exact definition can be found in [6]. The one-sided lower limit on the scale $\mathrm{M_S}$ at 95% confidence level is:

$$\mathrm{M_S} = 0.631 \text{ TeV}. \tag{7}$$

Examples of the data analysis at 189 GeV are shown in Figure 1 and Figure 2, where the SM predictions and the expectations from several manifestations of new phenomena are compared to the measurements of the L3 and OPAL collaborations, respectively. In these figures we plot the combined statistical and systematic errors; the theory uncertainty is not shown. In the area of the forward peak the theory uncertainty in the SM prediction starts to limit the precision of our study.

Contact Interactions

The standard framework, used in searches for deviations from the SM predictions, is the most general combination of helicity conserving dimension-6 operators [18]. In this scheme, new interactions beyond the Standard Model are characterised by a coupling strength, g, and by an energy scale, Λ, which can be viewed as the scale of compositeness. At energies much lower than Λ, we have an effective Lagrangian leading to four-fermion contact interactions.

Model	Amplitudes $[\eta_{LL}, \eta_{RR}, \eta_{LR}, \eta_{RL}]$	e^+e^- Λ_- [TeV]	e^+e^- Λ_+ [TeV]
LL	$[\pm1, 0, 0, 0]$	7.7	6.0
RR	$[0, \pm1, 0, 0]$	7.6	6.0
LR	$[0, 0, \pm1, 0]$	9.2	7.0
RL	$[0, 0, 0, \pm1]$	9.2	7.0
VV	$[\pm1, \pm1, \pm1, \pm1]$	16.2	13.0
AA	$[\pm1, \pm1, \mp1, \mp1]$	8.0	10.4
LL+RR	$[\pm1, \pm1, 0, 0]$	10.7	8.6
LR+RL	$[0, 0, \pm1, \pm1]$	12.9	10.1
LL−RR	$[\pm1, \mp1, 0, 0]$	4.3	4.2

Table 1: Results of contact interaction fits to Bhabha scattering. The numbers in brackets are the values of $[\eta_{LL}, \eta_{RR}, \eta_{LR}, \eta_{RL}]$ defining to which helicity amplitudes the contact interaction contributes. The models cover the interference of contact terms with single as well as with a combination of helicity amplitudes. The one–sided 95% confidence level lower limits on the parameters Λ_+ (Λ_-) given in TeV correspond to the upper (lower) sign of the parameters η, respectively.

The differential cross section for fermion-pair production in e^+e^- collisions can be decomposed in the usual way as:

$$\frac{d\sigma}{d\Omega} = \mathrm{SM}(s,t) + \varepsilon \cdot \mathrm{C_{Int}}(s,t) + \varepsilon^2 \cdot \mathrm{C_{CI}}(s,t) \tag{8}$$

where $\mathrm{SM}(s,t)$ is the Standard Model contribution, $\mathrm{C_{CI}}(s,t)$ comes from the contact interaction amplitude and $\mathrm{C_{Int}}(s,t)$ is the interference between the SM and the contact interaction terms. The exact form of these functions is given in [18]. By convention $\frac{g^2}{4\pi} = 1$ and $|\eta_{ij}| \leq 1$, where $(i,j = L,R)$ labels the helicity of the incoming and outgoing fermions. We define

$$\varepsilon = \frac{g^2}{4\pi}\frac{\mathrm{sign}(\eta)}{\Lambda^2} \tag{9}$$

where the sign of η enables to study both the cases of positive and negative interference.

As discussed in the previous section, the data from the LEP collaborations at 183 and 189 GeV show no statistically significant deviations from the SM predictions. In their absence, using the same technique we derive one-sided lower limits on the scale Λ of contact interactions at 95% confidence level. They are summarized in Table 1 and Figure 3. The results presented here improve on the limits obtained by individual LEP experiments [10, 13, 19, 20].

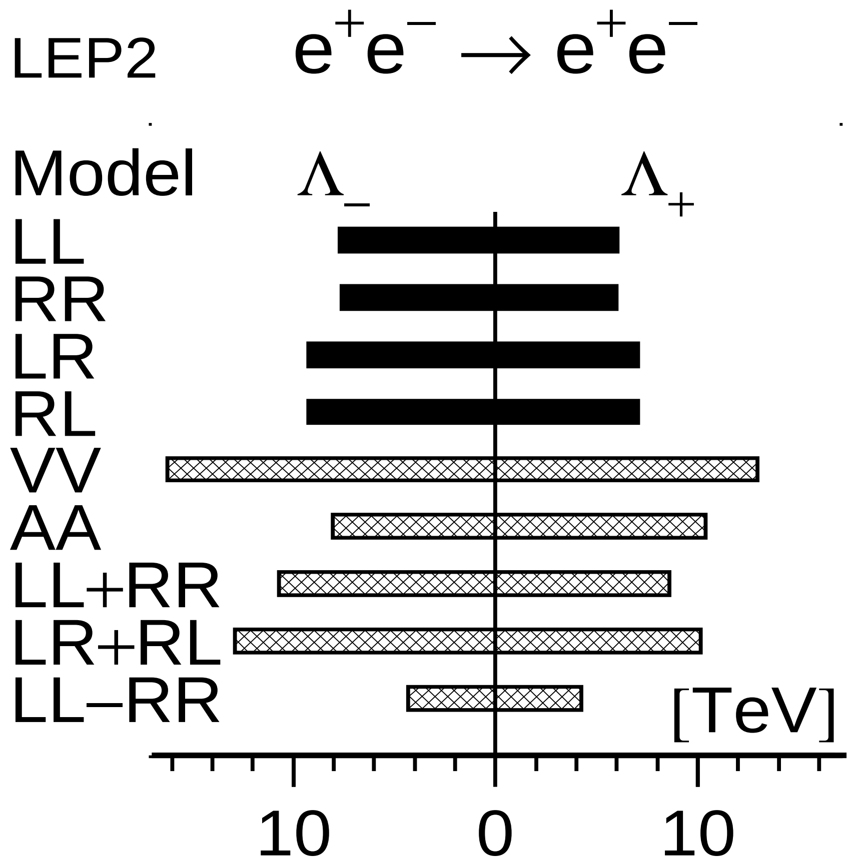

Figure 3: *One–sided 95% confidence level lower limits on the scale Λ_+ and Λ_- for contact interactions in Bhabha scattering.*

Electron Size

In the Standard Model leptons, quarks and gauge bosons are considered as point-like particles. A possible substructure or new interactions at as yet unexplored very high energies could manifest themselves as finite radii and anomalous magnetic dipole moments of these particles.

The high precision measurements of the magnetic dipole moment $(\mathrm{g}-2)_\mathrm{e}$ of the electron can be used to put stringent limits on the electron radius $\mathrm{r_e}$ [21, 22]. If non-standard contributions to $(\mathrm{g}-2)_\mathrm{e}$ scale linearly with the electron mass, the bound is $\mathrm{r_e} \sim 2 \cdot 10^{-23}$ m. On the other hand, if they scale quadratically with the electron mass, which is a natural consequence of chiral symmetry [21], the bound is reduced to $\mathrm{r_e} \sim 3 \cdot 10^{-18}$ m. In [22] the authors perform an analysis of the high precision data on the Z resonance, noting that while the assumption of

elementary photons is quite natural, the same is less obvious for the very massive Z bosons. In the pure electron case the limit is not competitive with the $(g-2)_e$ results.

Here we perform a new analysis based on the LEP2 data on Bhabha scattering, where again the photon exchange gives the dominating amplitudes both in the t- and s-channels, and good sensitivity to electron substructure can be expected. The differential cross section for fermion-pair production in e^+e^- collisions far above the Z is modified as:

$$\frac{d\sigma}{dQ^2} = (\frac{d\sigma}{dQ^2})_{SM} \cdot F_e^2(Q^2) \cdot F_f^2(Q^2) \tag{10}$$

where F_e and F_f are the form-factors of the initial (final) state fermions. They are parametrized in the standard way as [22]:

$$F(Q^2) = 1 + \frac{1}{6} \cdot Q^2 \cdot r^2 \tag{11}$$

where Q^2 is the Mandelstam variable s or t for s- or t-channel exchange, and r^2 is the mean-square radius of the fermions. This formalism is a convenient way to estimate the electron size in the case where the product $Q^2 \cdot r^2$ is small.

From the data of the LEP collaborations at 183 and 189 GeV we extract the following upper limit on the electron radius at 95% confidence level:

$$r_e < 2.8 \cdot 10^{-19} \text{ m}. \tag{12}$$

This limit is one order of magnitude lower than the limit derived from $(g-2)_e$ measurements in the case where the deviations from the SM of the magnetic dipole moment of the electron depend quadratically on its mass.

High energy analyses have been performed in interactions involving electrons and quarks, assuming a single form-factor for all fermions. The H1 collaboration at HERA uses deep inelastic scattering and obtains a limit of $r < 26 \cdot 10^{-19}$ m at 95 % confidence level [23]. The CDF collaboration at the TEVATRON studies the Drell-Yan process to put a limit of $r < 5.6 \cdot 10^{-19}$ m at 95 % confidence level [24].

Discussion

The search for TeV strings motivates a fresh look at Bhabha scattering. In the model analyzed here the string realization of quantum gravity is manifested as a form-factor which modifies the differential cross section. The lower limit obtained in our analysis of LEP2 data is $M_S = 0.631$ TeV. In [6] from the study of virtual graviton exchange in gravity models with large extra dimensions we obtained a lower limit on their scale of $\Lambda_T = 1.412$ TeV for positive inteference ($\lambda = +1$) [2]. As noted in [8], the gravity scale is between $1.6 \div 3.0 \cdot M_S$, depending on the coupling strength. The results on the gravity scale from [6] and on the string scale from this analysis agree well with each other.

It is interesting to note that our study of the electron size also leads to form-factors modifying the differential cross section, but with opposite sign. The limit derived here, $r_e < 2.8 \cdot 10^{-19}$ m, becomes $M_r > 0.705$ TeV, if translated to a mass scale. This is a reflection of the similar magnitude of the effects at LEP2 energies in both cases, even if the physics mechanisms involved are different.

In the framework of contact interactions very stringent bounds exceeding 10 TeV are obtained. When interpreting the physical meaning of these limits, we should remember that a

[2] This value of Λ_T corresponds, depending on the convention, also to a gravity scale $M_s = 1.261$ TeV. The gravity scale with subscript small s should not be confused with the string scale M_S, studied here.

strong coupling $\frac{g^2}{4\pi} = 1$ for the novel interactions is postulated by convention. If we assume a coupling of electromagnetic strength, the limits can be translated:

$$\Lambda' = \sqrt{\alpha_{\mathrm{QED}}} \cdot \Lambda = 0.085 \cdot \Lambda \tag{13}$$

where we have used the value of the fine structure constant and ignored the small effect of a running α_{QED}. For instance the VV model with positive interference gives effects similar to the ones resulting from a finite electron size, as shown in Figure 1 and Figure 2. The limit for the VV model translates as follows:

$$\Lambda_+ = 13.0 \text{ TeV} \Rightarrow \Lambda' = 1.1 \text{ TeV} \Rightarrow \mathrm{r} = 1.8 \cdot 10^{-19} \text{ m}. \tag{14}$$

This results is comparable with the upper limit for electron substructure, derived using form-factors.

The measurements of Bhabha scattering above the Z resonance confirm the predictions of the Standard Model and reach already a similar level of precision as the best theoretical tools available. In order to fully exploit the physics potential of the large data samples collected during the LEP running in 1999 and expected in 2000, improved theory predictions are very desirable. Bhabha scattering is a probe, sensitive enough to provide a first window to new physics at the TeV scale.

Acknowledgements

The author is grateful to A. Böhm, M. Peskin and I. Antoniadis for valuable discussions.

References

[1] N.Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. **B 429** (1998) 263

[2] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. **B 436** (1998) 257

[3] N.Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Rev. **D 59** (1999) 086004

[4] L3 Collaboration, M.Acciarri *et al.*, Phys. Lett. **B 464** (1999) 135

[5] L3 Collaboration, M.Acciarri *et al.*, Phys. Lett. **B 470** (1999) 281

[6] D. Bourilkov, J. High Energy Phys. **08** (1999) 006 ; hep–ph/9907380

[7] E. Accomando, I. Antoniadis and K. Benakli, hep-ph/9912287

[8] S. Cullen, M. Perelstein and M. Peskin, hep-ph/0001166

[9] D. Bourilkov, LEP review talk, XXXIII Rencontres de Moriond, France, 1998; published in the proceedings ed. by J. Trân Thanh Vân, Edition Frontiers, Paris, 1999, page 139; hep-ex/9806027

[10] ALEPH Collaboration, Preprint CERN-EP/99-042, CERN, 1999, submitted to Eur. Phys. J. C

[11] L3 Collaboration, Preprint CERN-EP/99-181, CERN, 1999, submitted to Phys. Lett. B

[12] OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. C6(1999)1

[13] OPAL Collaboration, Preprint CERN-EP/99-097, CERN, 1999, accepted by Eur. Phys. J. C

[14] S. Jadach, W. Placzek and B.Ward, Phys. Lett. **B390** (1997) 298

[15] G. Montagna, O. Nicrosini, G. Passarino, F. Piccinini and R. Pittau, Nucl. Phys. **B 401** (1993) 3

[16] R. Kleiss *et al.*, Z Physics at LEP 1, volume 3, (CERN, 1989)

[17] L3 Collaboration, M.Acciarri *et al.*, Phys. Lett. **B 414** (1997) 373

[18] E. Eichten, K. Lane and M. Peskin, Phys. Rev. Lett. **50** (1983) 811

[19] L3 Collaboration, M.Acciarri *et al.*, Phys. Lett. **B 433** (1998) 163

[20] DELPHI Collaboration, P.Abreu *et al.*, Eur. Phys. J. **C11** (1999) 383

[21] S.J. Brodsky and S.D. Drell, Phys. Rev. **D22** (1980) 2236

[22] G. Köpp, D. Schaile, M. Spira and P.M. Zerwas, Zeit. für Phys. **C65** (1995) 545

[23] H1 Collaboration, S.Aid *et al.*, Phys. Lett. **B 353** (1995) 578

[24] CDF Collaboration, F.Abe *et al.*, Phys. Rev. Lett. **79** (1997) 2198.